

Massive Stellar Clusters
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Star Clusters in Local Group Galaxies – Impact of Environment on Their Evolution and Survival

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Abstract. Star clusters are found in $\sim 40\%$ of the Local Group galaxies. Their properties are reviewed. The impact of galaxy environment on the evolution and survival of star clusters is discussed. Possible evidence for cluster formation triggered by galaxy interactions, gradients in cluster size, metallicity and stellar content with galactocentric radius and variations as a function of galaxy type are briefly summarized.

1. Introduction

Star clusters in Local Group galaxies comprise a wide range of roughly coeval stellar agglomerates ranging from globular clusters to associations, from very metal-poor objects to clusters with solar and higher metallicity, and from ancient populations to embedded young clusters. Three basic types of such clusterings are observed: globular clusters, open clusters, and associations.

1.1. Globular Clusters

Globular clusters are centrally concentrated, spherical systems with masses of $4.2 \lesssim \log M[M_\odot] \lesssim 6.6$ and tidal radii ranging from ~ 10 to ~ 100 pc. They are bound, long-lived ($\gtrsim 10$ Gyr) objects whose lifetimes may extend to a Hubble time or beyond, though due to various efficient destruction mechanisms the presently observed globulars are likely just a lower limit of the initial number of globular clusters. Globular clusters have been observed in all known types of galaxies, but many of the less massive galaxies do not contain globular clusters.

Thirteen of the 36 Local Group galaxies have globular clusters. The most massive, most luminous ($M_V = -10^m 55$) globular cluster in the Local Group is the old, metal-rich, elliptical globular Mayall II (or G1) in M31 (Rich et al. 1996). In contrast, the faintest ($M_V \sim 0^m 2$), least massive globular currently known is AM-4, a distant old Galactic halo globular cluster (Inman & Carney 1987).

1.2. Open Clusters

Open clusters have masses of $3 \lesssim \log M[M_\odot] \lesssim 5$ and radii of 1 to 20 pc. Most Milky Way open clusters survive for only ~ 200 Myr (Janes, Tilley, & Lyngå 1988), although there are long-lived open clusters with ages of several Gyr (Phelps, Janes, & Montgomery 1994). Loose, extended open clusters are

dominant in spiral galaxies like the Milky Way, while the Magellanic Clouds contain a large number of blue, compact, populous clusters. Open clusters were identified in $\sim 42\%$ of the Local Group galaxies. None were found in dwarf spheroidals (dSphs), which are dominated by populations older than a few Gyr.

The oldest open clusters (e.g., NGC 6791: ~ 8 Gyr; Chaboyer, Green, & Liebert 1999) and the youngest globulars (e.g., Ter 7: ~ 8 Gyr; Buonanno et al. 1998a) in the Local Group overlap in age. The distinction between massive open clusters and low-mass globular clusters is somewhat arbitrary and largely based on age. Bound objects that survive for more than 10 Gyr are generally called globulars even though they may resemble sparse open clusters.

1.3. Super Star Clusters

Super star clusters are young populous clusters with masses exceeding several $10^4 M_\odot$ within a radius of 1–2 pc. They may be progenitors of globular clusters. The most massive super star clusters are found in interacting and starburst galaxies (e.g., Schweizer & Seitzer 1998, Gallagher & Smith 1999). Super star clusters are often located in giant H II regions or as nuclear star clusters near the centers of massive galaxies. Some may be progenitors of globular clusters. Not every giant H II region harbors a super star cluster though.

Only a few, low-mass super star clusters are known in the Local Group. Giant H II regions such as 30 Doradus in the Large Magellanic Cloud (LMC) and NGC 3603 in the Milky Way both contain starburst clusters, which interestingly show evidence for the formation of low-mass stars (e.g., Brandl et al. 1999) despite the presence of many very massive stars such as O3 and main-sequence Wolf-Rayet stars. If the R 136 cluster in 30 Dor can remain bound over a Hubble time it will evolve into a low-mass globular cluster. Some of the populous LMC clusters might survive as well for a Hubble time (Goodwin 1997a).

The Quintuplet and Arches clusters near the Galactic center (Figer et al. 1999) are examples for nuclear clusters in the Local Group. They may have formed through colliding giant molecular clouds and are expected to have a limited lifetime due to the strong tidal forces of their environment.

1.4. Associations

Star formation in giant molecular clouds leads usually to the formation of associations and/or open clusters, which appear to be the major contributors to a galaxy's field population. Associations are extended, unbound, coeval groups of stars with radii of $\lesssim 100$ pc. They disperse on time scales of ~ 100 Myr. Associations mark spiral arms in spiral galaxies. They may be located within or at the edges of shells and supershells in spirals and irregulars. Often they are embedded in hierarchical structures of similar age such as stellar aggregates (~ 250 pc radius) and star complexes (~ 600 pc radius; Efremov, Ivanov, & Nikolov 1987). It seems reasonable to assume that associations were present in all types of galaxies during and after episodes of star formation.

In the Local Group associations can be found in all galaxies with current star formation. Both open clusters and associations generally have initial mass functions (IMFs) consistent with a Salpeter slope for high and intermediate-mass stars (Massey, Johnson, & DeGioia-Eastwood 1995a, Massey et al. 1995b).

2. Star Clusters in the Local Group

The global properties of the star clusters in Local Group galaxies are summarized in Table 1. Within a zero-velocity surface of 1.2 Mpc (Courteau & van den Bergh) around the Local Group barycenter 36 galaxies are currently known. In less than half of these globular or open clusters were detected. While past surveys established that the majority of the least massive galaxies, the dSphs, do not contain star clusters, the census for more massive galaxies is still incomplete.

Table 1. Global Properties of Star Clusters in the Local Group

| Galaxy | Type | M_V [mag] | N_{GC} | S_N | Ages [Gyr] | [Fe/H] [dex] | N_{OC} | Ages [Gyr] | [Fe/H] [dex] |
|----------|-------------|----------------|------------------|--------|---------------|--------------------------|--------------------|----------------------|--------------------------|
| M31 | Sb I-II | -21.2 | ~600 | 2: | ≤ 15 | -2.5 - 0.4 ^a | many | .004-? | ? |
| Galaxy | S(B)bc I-II | -20.9 | ~160 | 0.7 | 8-15 | -2.5 - 0.4 | >1000 | .001-9 | -1.0 - 0.4 |
| M33 | Sc II-III | -18.9 | ~25 ^b | 0.7: | ≤ 12 | -3.0 - -0.8 ^c | > 600 ^c | .004-? | ? |
| LMC | Ir III-IV | -18.5 | ~13 | 0.5 | 9-15 | -2.3 - -1.2 ^d | >4000 | .001-4 ^e | -1.4 - -0.1 ^f |
| SMC | Ir IV/IV-V | -17.1 | 1 | 0.1 | 12 | -1.4 | >2000 | .001-10 | -1.4 - -0.5 |
| IC 10 | Ir IV: | -16.3 | 0 | 0 | — | — | several | ? | ? |
| NGC 6822 | Ir IV-V | -16.0 | 1 | 0.4 | ~11 | -2.0 ^g | ~30 ^h | 2 (VII) ^g | -1.0 (VII) ^g |
| IC 1613 | Ir V | -15.3 | 0 | 0 | — | — | > 6 ⁱ | .01-? | ? |
| WLM | Ir IV-V | -14.4 | 1 | 1.7 | 15 | -1.5 ^j | ? | ? | ? |
| NGC 205 | Sph | -16.4 | ~14 ^k | ~3.9 | ? | -1.9 - -1.3 ^l | ~2 ^m | ~.05 ⁿ | ? |
| NGC 185 | Sph | -15.6 | ~8 ^k | ~4.6 | ? | -2.5 - -1.2 ^l | some ^k | ? | ? |
| NGC 147 | Sph | -15.1 | ~4 ⁿ | ~3.6 | ? | -2.5 - -1.9 ^l | ? | ? | ? |
| Sgr | dSph(t) | -13.8: | ~4 | ~12.1: | 8-15 | -2.0 - -0.4 ^o | 0 | — | — |
| Forn | dSph | -13.1 | 5 | 22.8 | 12-15 | -2.2 - -1.8 ^p | 0 | — | — |
| And I | dSph | -11.8 | 1 | 20.9 | old | -1.4 ^q | 0 | — | — |

Notes: Galaxy types (Col. 2) and M_V (Col. 3) were taken from Courteau & van den Bergh (1999). N_{GC} and N_{OC} (Cols. 4 & 7) denote the number of globular clusters and open clusters, respectively. All quoted ages assume an oldest age of 15 Gyr. S_N is the specific globular cluster frequency.

References: ^aBarmby et al. 2000, astro-ph/9911152; ^bChristian & Schommer (1988, AJ, 95, 704); ^cChandar et al. 1999, ApJ, 517, 668; ^dOlsen et al. 1998, MNRAS, 300, 665; ^eSarajedini 1998, AJ, 116, 738; ^fJasniewicz & Thévenin 1994, A&A, 282, 717; ^gCohen & Blakeslee (1998, AJ, 115, 2356); ^hHodge (1977, ApJS, 33, 69); ⁱWyder et al. (2000, 33rd ESLAB Symp., in press); ^jHodge et al. (1999, ApJ, 521, 577); ^kGeisler et al. (1999, IAU Symp. 192, p. 231); ^lDa Costa & Mould (1988, ApJ, 334, 159); ^mCappellari et al. (1999, ApJ, 515, L17); ⁿHodge (1976, AJ, 81, 25). ^oDa Costa & Armandroff (1995, AJ, 109, 2533); ^pBuonanno et al. (1998, ApJ, 501, L33); ^qGrebel et al. (2000a, in prep.).

3. Environmental Effects and Interactions Between Galaxies

Generally, the number of globular clusters is larger in the more massive galaxies, while the few globular clusters in faint dSphs lead to high specific frequencies S_N (i.e., the number of globulars, N_{GC} , normalized by parent galaxy luminosity; $S_N = N_{GC} \cdot 10^{0.4(M_V+15)}$, Harris & van den Bergh 1981).

3.1. Tidal Stripping

The orbital decay times of globular clusters in dSph galaxies are of the order of only a few Gyr (Hernandez & Gilmore 1998). While in Sagittarius and Fornax one of the globulars lies near the projected galaxy center, both dSphs show spatially extended globular cluster systems. This as well as the puzzling present-day lack of gas suggests that they underwent significant mass loss (Oh, Lin, &

Richer 2000). The detection of extratidal stars suggests that tidal stripping may have reduced some dSphs to as little as 1% of their original mass (Majewski et al. 2000). This might explain the inflated S_N measured today.

The dSph And I is the least massive galaxy in which a globular cluster has been detected to-date (Grebel, Dolphin, & Guhathakurta 2000a). Its faint, sparse globular resembles Galactic outer halo globulars and is located just beyond the galaxy’s core radius. And I is another good candidate for tidal stripping due to its close proximity to M31 (45–85 kpc, Da Costa et al. 1996).

Conversely, some globular clusters may have been stripped from dwarf galaxies by more massive galaxies, or may be the cores of accreted nucleated dwarf galaxies (e.g., Bassino, Muzzio, & Rabolli 1994). Its abundance spread and possible age range suggest that the Milky Way’s most massive globular, ω Cen, may be the result of such an evolution (e.g., Hughes & Wallerstein 2000).

3.2. Cluster Formation Triggered By Galaxy Interactions?

The Magellanic Clouds interact with each other and with the Milky Way, and stand out through their excess in young populous clusters. No such large numbers are observed in the other, less massive Local Group irregulars, none of which are close to a massive spiral. The field star formation history of the Magellanic Clouds is fairly continuous (Holtzman et al. 1999), but the LMC shows a pronounced peak in cluster formation 1–2 Gyr ago, which coincides with the second last close encounters with the Milky Way (Girardi et al. 1995). Curiously the Small Magellanic Cloud (SMC) does not show a corresponding peak at this age. However, the cluster age distributions of LMC and SMC both peak at 100–200 Myr (Grebel et al. 2000b), which coincides with the last perigalacticon and the last close encounter between the Magellanic Clouds (Gardiner, Sawa, & Fujimoto 1994). This appears to suggest that the recent increases in cluster formation may have been partially interaction-triggered.

4. Cluster Destruction Through Intragalactic Environment

Gnedin & Ostriker’s (1997) “vital diagrams” summarize the dominant effects of globular cluster destruction (see also Gerhard, these proceedings) in the Milky Way: relaxation, tidal shocks through disk and bulge passages, and dynamical friction as a function of globular cluster mass and half-mass radius. At small Galactocentric distances only fairly massive, compact globular clusters can survive for more than a Hubble time. This correlates well with the observed increase in globular cluster half-light radii with Galactocentric distance (van den Bergh 1994a), while the lack of compact clusters at large distances remains puzzling. Goodwin (1997b) suggests that for a given Galactocentric radius, IMF, and star formation efficiency (SFE), the survival of a cluster depends on its central density at the time of formation (see McLaughlin’s contribution for more on SFEs).

The short (0.2 Gyr) lifetime of Milky Way open clusters is believed to be partially due to interactions with giant molecular clouds, which destroy open clusters within the solar radius (Wielen 1991). In the Magellanic Clouds, a less violent dynamical environment, open cluster life expectancies are much longer (median age 0.9 Gyr (SMC) and 1.1 Gyr (LMC); Hodge 1988).

5. Cluster Properties as Function of Environment

5.1. The Oldest Star Clusters in the Local Group

While absolute and relative age determinations for globular clusters are plagued by a number of uncertainties (Stetson, VandenBerg, & Bolte 1996; Sarajedini, Chaboyer, & Demarque 1997), there is growing consensus that Galactic globular clusters show age differences ≥ 5 Gyr. Age values listed in Table 1 refer to an arbitrarily chosen oldest age of 15 Gyr. The oldest globular clusters in the Milky Way, the LMC (Olsen et al. 1998; Johnson et al. 2000), Sagittarius (Montegriffo et al. 1998), and Fornax (Buonanno et al. 1998b) formed at the same time, while cluster formation began ~ 3 Gyr later in the SMC (Mighell, Sarajedini, & French 1998) and M33 (Sarajedini et al. 1998). These differences are not obviously correlated with galaxy mass, type, or location.

5.2. Radial Abundance Gradients

The globular cluster systems of Local Group spirals show an overall radial abundance gradient in the sense that the central (bulge) regions contain a range of abundances including very metal-rich clusters (Barbuy, Bica, & Ortolani 1998), while the mean metallicities decrease with increasing galactocentric distance. The LMC appears to show similar behavior (Da Costa 2000).

5.3. Cluster Shapes and Sizes

Due to the weaker tidal field of the LMC, its clusters can retain higher ellipticities longer (Goodwin 1997c). At a given galactocentric distance the LMC globular clusters tend to be larger than Galactic globulars, and in both Milky Way and LMC half-light radii (r_h) increase with galactocentric distance (van den Bergh 2000 and Sect. 4). Galactic globulars on nearly circular orbits are systematically larger (van den Bergh 1994a), while clusters on retrograde orbits are smaller than other globulars, indicative of preferred tidal stripping (van den Bergh 1994b). One could speculate that the small r_h values of Fornax's globulars indicate that this dSph was initially much more massive. Van den Bergh (1994a) interprets the small r_h values as evidence against accretion of globular clusters from disintegrating dSphs by the Galactic halo. In contrast, the large r_h of And I's globular cluster (~ 10 pc) is comparable to that of Galactic outer halo globular clusters (Grebel et al. 2000a).

5.4. Stellar Content

The horizontal branch (HB) morphologies of inner LMC globular clusters resemble those of inner Galactic halo globulars, while outer LMC globulars show the same second-parameter effects as their Galactic counterparts (Johnson et al. 2000). Two of the old Fornax globular clusters show clear second-parameter HB variations (Smith et al. 1996, Buonanno et al. 1998b). This shows not only that second-parameter globulars in dwarfs can be as old as the oldest Galactic halo globulars, but also that accretion of globular clusters from disintegrating dwarfs (a mechanism proposed to explain the metal-poor, red HB clusters in the outer Galactic halo) would contribute both types of globulars to the Milky Way halo.

For a discussion of the metallicity dependence of the blue-to-red supergiant ratio in young Galactic and Magellanic clusters we refer to Langer & Maeder (1995). A possible metallicity dependence of Be star fractions and rotation in young clusters in these galaxies is discussed in Maeder, Grebel, & Mermilliod (1999).

6. Summary

In about 40% of the Local Group galaxies star clusters have been detected so far, but the census is still incomplete. Several (but not all) Local Group galaxies seem to share a common epoch of the earliest globular cluster formation. The most massive galaxies show a tendency for rapid enrichment in their oldest cluster population near their centers as compared to clusters at larger galactocentric radii. The galactocentric dependence of cluster sizes and HB morphology may be intrinsic to the globular cluster formation process rather than to the accretion of dwarf galaxies. The observed properties of the globular clusters in the least massive dwarfs suggest that their parent galaxies may originally have been substantially more massive. Cluster destruction mechanisms and time scales are a function of galaxy environment and galaxy mass. The most recent enhancement of star cluster formation in the Magellanic Clouds may have been triggered by their close encounter with each other and the Milky Way.

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